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COMMENTS ON A TECHNIQUE TO MEASURE MIXING ENERGY AVAILABLE FOR OILSPILL DISPERSION

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ABSTRACT

Turbulence is the critical process in the dispersion of spilled oil into the water column. The Centre for Cold Ocean Resources Engineering (C-CORE) at Memorial University of Newfoundland, in cooperation with the Arctic Marine Oilspill Program (AMOP), has been investigating the use of a recently developed turbulence measuring device. It is hoped that this device may allow comparison of turbulent energy levels in various different dispersant test facilities and in the ocean. Preliminary results of turbulence measurements obtained during the development period are reported here.

INTRODUCTION

Chemical dispersants used to break up spilled oil are usually tested in laboratory facilities because of the logistical difficulties and environmental impact of field studies. Laboratory tests also permit experimental control of the parameters involved, chief amongst these being the energy available to break up and down-mix the oil once the dispersant has reduced the surface tension. In order to establish standardized tests for dispersants, it is necessary to know how much mixing energy is made available during each test. It would also be useful to compare the mixing energy available during laboratory test to that available in the open ocean under various conditions.

C-CORE has undertaken to develop a simple method that will measure the mixing energy present using an electrochemical anemometer, described in detail in C-CORE (1981) and Reimer (1982). The anemometer measures the rate of transport of dissolved oxygen in the surface layers of seawater and gives a voltage output that is proportional to the 2/5th power of the speed of water past the probe. (It is assumed that the seawater is saturated so that the oxygen concentration is constant.) It can detect speeds as low as 1 mm/s and responds to a change in speed in less than 1/500th of a second. It senses speed with two small electrodes, one silver and one platinum, spaced about 3 cm apart, and can therefore sense mixing events of centimetre dimensions.

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One must now attempt to define "mixing energy". The Naval Underwater Systems Center (NUSC) in Newport, R.I., has made an extensive study of parameters affecting oil mixing in the sea (Shonting et al., 1979) and refers to the kinetic energy associated with wave turbulence. In particular, they refer to the kinetic energy variances of the water motions (turbulent energy) and the power spectral density of these motions. These are defined respectively as:

$$E_T = \rho/2 \, [\langle \vec{v} \rangle - \vec{v}(t)]^2 \qquad (1)$$

and

$$W(\nu) = \rho/2 \, |F(\nu)|^2 \qquad (2)$$

where:

$$F(\nu) = 1/T \int_0^T |\vec{v}(t)| e^{i2\pi\nu t} \, dt \qquad (3)$$

ρ is the density of the water, E_T is the instantaneous kinetic energy variance per unit volume of water, $\langle \vec{v} \rangle$ is the average velocity over some period of time, and $\vec{v}(t)$ is the instantaneous velocity past a sensor at time t. $F(\nu)$ is the Fourier transform of the speed $|\vec{v}(t)|$, and $W(\nu)$ is the power spectral density of the water motions.

What do these quantities really mean? First, examine E_T. If $\vec{v}$ is averaged over a long period of time, such as an hour or so, then $\langle \vec{v} \rangle$ would be the velocity of the mean current past the sensor. Now, let an ocean wave traverse the sensor, say the swell in the open ocean. The velocity of the water molecules in the swell past the probe would, at any instant, be different than the mean current velocity, since the swell is superimposed on the mean current. Hence, this energy would be significant and might well dominate E_T. However, motions due to the swell are not turbulent and field observations do not indicate that the swell contributes to the dispersion of oil. Indeed, it is the opinion of the authors that small-scale events such as breakers are the dominant dispersion mechanism. This comes from visual observations of the October 1981 offshore dispersant trial near St. John's, Newfoundland and is supported by the NUSC report. Hence, one must be careful to determine $\langle \vec{v} \rangle$ over short time scales if E_T is to reflect the turbulent kinetic energy. This represents an operational constraint on the determination of E_T.

The Spectral Energy Density $W(\nu)$ refers to the square modulus of the Fourier transform $F(\nu)$ of the speed $|\vec{v}(t)|$. In simpler terms, it assumes the water motion to be a superposition of periodic motions (a well-known fact in mathematics). That is, any motion in the water, turbulent or not, is the superposition of different water waves plus the mean current. $W(\nu)$ is just the energy in each of these waves given as a function of the wave's frequency ν. For example, the spectral energy density of a 20-second swell with 2- to 5-second waves imposed on it might resemble Figure 1. This is useful because under more turbulent conditions the spectral energy density grows a tail (Figure 2) (Shonting et al., 1979). The premise is that in more turbulent sea conditions the small-scale eddies caused by breaking waves begin to appear, giving a high-frequency tail to $W(\nu)$. A knowledge of $W(\nu)$ makes estimation of average turbulent energy $\bar{E}_T$ quite easy. $\bar{E}_T$ is just the area under the high frequency tail of $W(\nu)$:

$$\bar{E}_T = \rho/2 \int_{\nu_{cutoff}}^{\infty} W(\nu)\, d\nu \qquad (4)$$

ν_{cutoff} is the frequency where the turbulent tail starts.

Equation (4) may be considered an operational definition of the turbulent kinetic energy. Even so, analysis of the data in these experiments often required careful interpretation of the above formulae. This will be dealt with later.

THE EXPERIMENTS

Three different environments have been used so far in testing of the anemometer probes. The first set of data was collected at Cape Hatt, Baffin Island, during the Baffin Island Oilspill Project (BIOS) in September, 1980. A single anemometer probe was used, usually near shore in 1 or 2 metres of water, though some data were taken in 150 metres of water. The probe depth was varied, although usually the probe was kept near the surface. Conditions were relatively calm. During worst weather, 30 knot winds resulted in swells estimated at 60 cm in the vicinity of the probe.

Further tests were carried out in Dr. D. Mackay's labs at the Institute for Environmental Studies, University of Toronto. A single probe was used in a dispersant test tank using a ring-type wave generator driven at one (adjustable) frequency. Waves of only one frequency existed (along with harmonics) and the tank was said to be in a resonant mode. Total energy input was varied over a relatively small range.

Field tests were also carried out in Logy Bay, a small bay which faces the open ocean near St. John's, Newfoundland. This bay is known for particularly rough sea conditions. The tests were conducted over four days in March, 1982. Four probes were used, mounted two-by-two 30 cm deep and

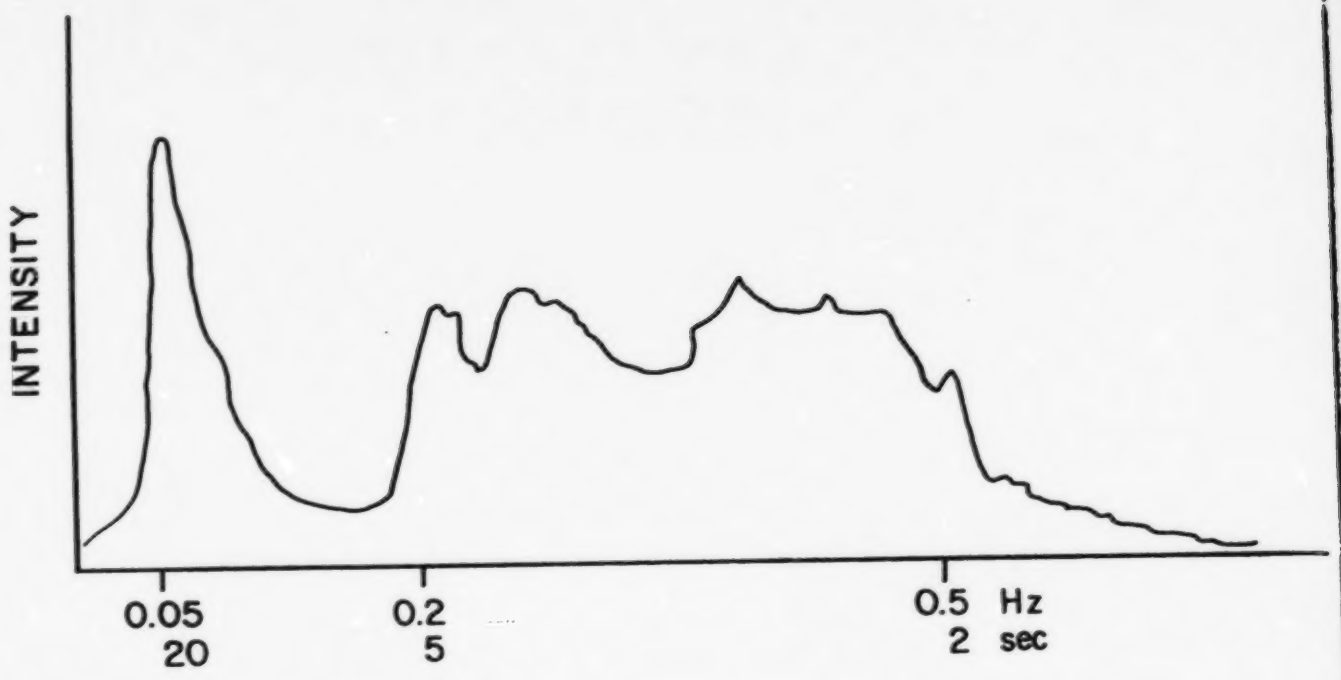

FIGURE 1 HYPOTHETICAL SPECTRUM SHOWING POWER IN THE 0.2 TO 0.5 Hz RANGE AND POWER AROUND 0.05 Hz AS MIGHT RESEMBLE A 20-SECOND SWELL WITH 2- TO 5-SECOND WAVES SUPERIMPOSED ON IT

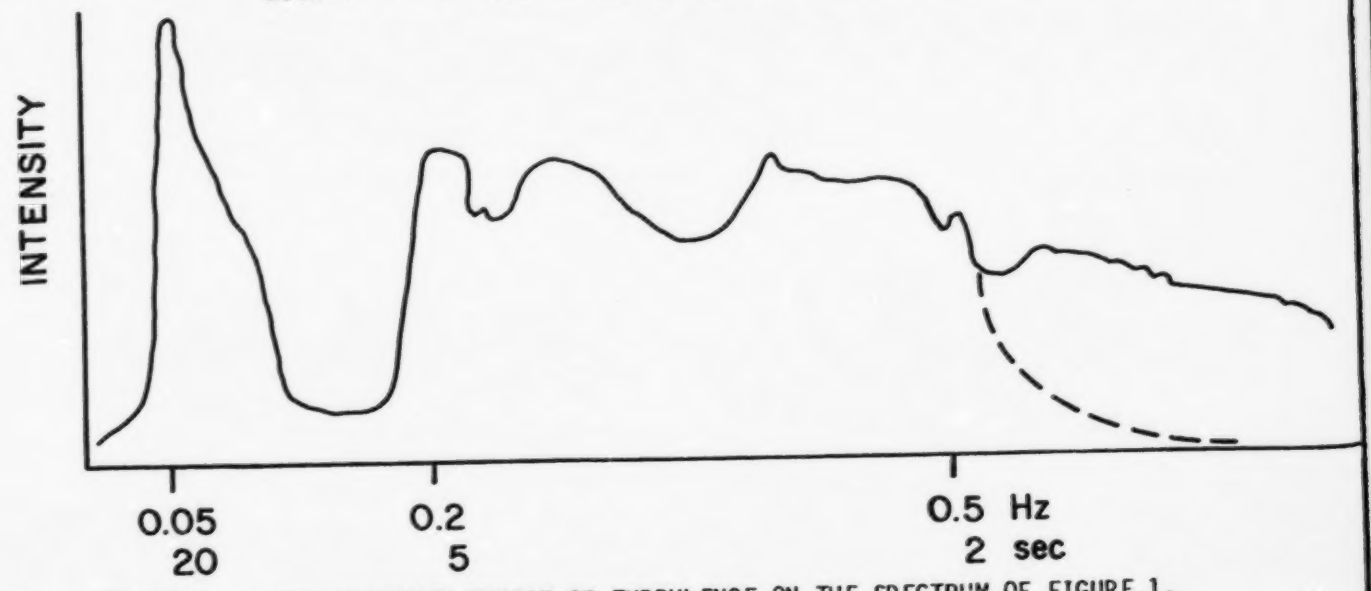

FIGURE 2 THE EXPECTED EFFECT OF TURBULENCE ON THE SPECTRUM OF FIGURE 1. The dotted line represents the curve of Figure 1.

120 cm deep on a 4-m high aluminum spar buoy (Figure 3). During design of the buoy, an attempt was made to keep the resonant frequencies of pitch and heave below 0.5 Hz and still allow it to be easily deployed by two men in a rubber dinghy. However, because the weight of the buoy was to be kept as low as possible, the buoy's resonances were close to 0.5 Hz. This didn't appear to cause any serious difficulties.

At each depth, one anemometer had a vertical duct while the other was left unducted. It was thought that the ducted probe would give the vertical component of turbulent water motion and the motion of the buoy with respect to long period waves while the unducted probe would measure the speed of the water independent of direction. The horizontal component of water motion could be deduced if the vertical component were removed from the total speed.

The logistics of this experiment were significantly more difficult than for the other tests. The buoy was moored to a float about 100 metres from shore and could move freely about this float. The float was secured to a 450-kg anchor in 120 metres of water. The four anemometer channels were fed into a multiplexer and transmitted on one FM radio channel to a receiver and instrumentation tape recorder (HP3968) on land. The telemetry link was designed by Instrumar Ltd. of St. John's, Newfoundland. The data were then played back, demodulated, digitized, and analyzed on a Hewlett Packard Fourier Analyzer. Over three days of data were recorded in weather conditions that ranged from calm (no whitecaps, swells estimated from 1 to 2 m) to quite rough (whitecaps, swells estimated at 4 m, strong onshore winds).

Data Analysis and Results

Figure 4 is typical of the results obtained from the dispersant test tank at the University of Toronto. When compared to Figure 7 (Cape Hatt spectra), marked differences are observed. The resonant excitation and its overtones are extremely clear in the power spectrum from the tank. While it has not been demonstrated that this mode of operation is adverse to successful dispersion of oil, there is little or no turbulence present in this situation. Instead, there is one standing wave mode, like an ocean wave but of higher frequency. This raises the question: Do dispersants work as well in this environment as they would in a truly turbulent environment? Hence, a dispersant that is unsuccessful in the lab might still work in the field. To avoid this type of problem, one must know if this sort of lab environment is comparable to the field environment. This is one objective of these turbulence measurements.

Since experimental control is facilitated under wave tank conditions, the records from the University of Toronto are clean and easily interpreted. The total power levels are also easy to obtain. This suggests that the anemometer may be quite useful for comparing conditions in one tank or during one test to those in another tank or during another test. For

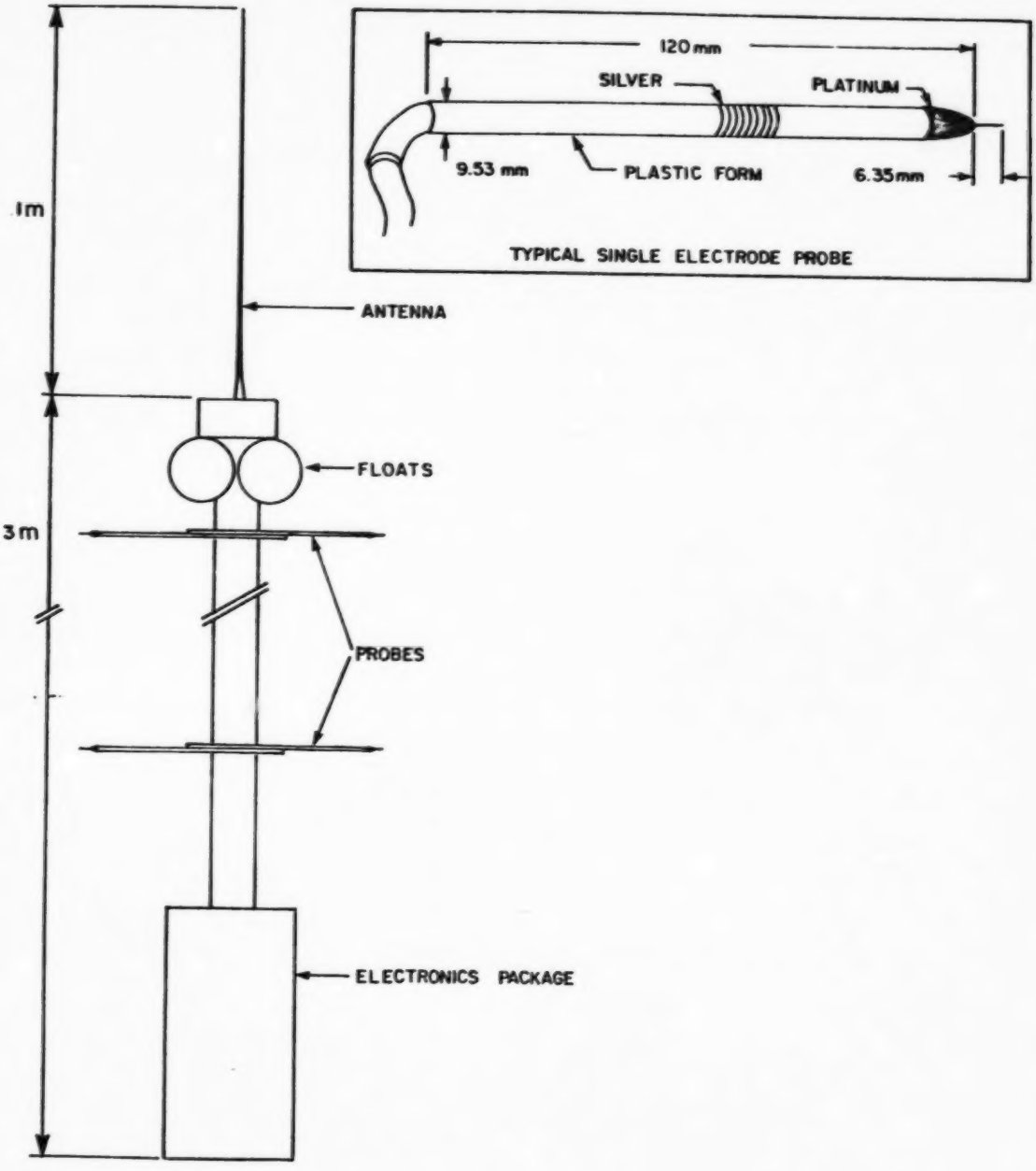

FIGURE 3 SCHEMATIC DIAGRAM OF SPAR BUOY USED IN LOGY BAY. THE PROBES ARE MOUNTED AT THE ENDS OF THE ARMS AT 30 cm AND 120 cm DEPTH. At each depth, one probe has a vertical duct on it (not shown) while one probe remains unducted. Inset shows anemometer probe.

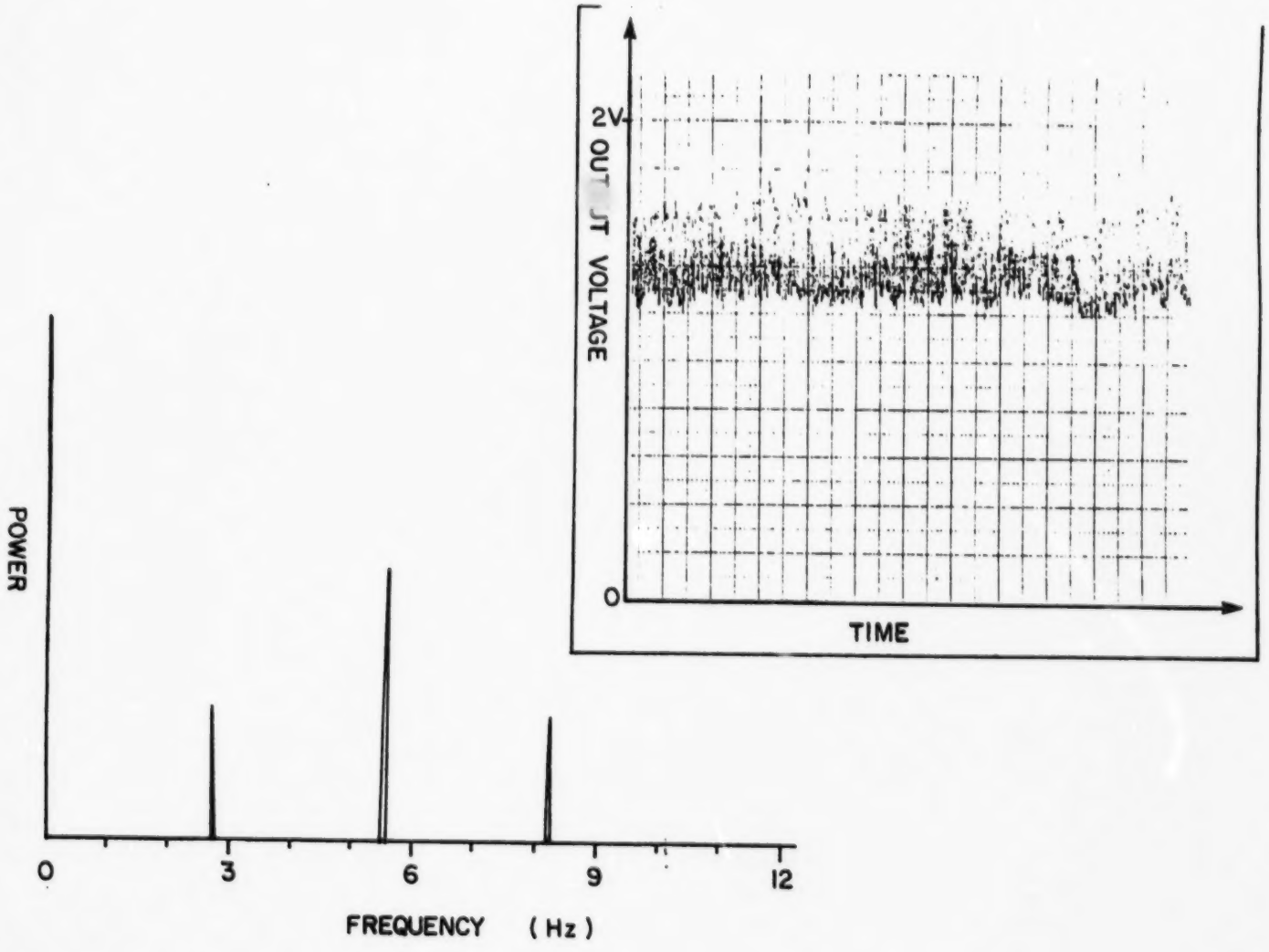

FIGURE 4 SAMPLE POWER SPECTRUM FROM DISPERSANT TEST TANK AT THE UNIVERSITY OF TORONTO. From this spectrum, it is obvious that 2.8 Hz waves and their overtones were the only significant energy present.

example, it would be possible to say that dispersants are successful in a given test once a certain energy threshold is attained. Alternatively, one might be able to say that dispersants perform better in one tank than in another because the power spectrum indicates the presence of turbulent motion.

The system also performed well in a small weir-produced eddy constructed at C-CORE; it gave a highly energetic and very smooth spectrum in the 0 to 15 Hertz range (Figure 5). This suggested that the system would work well in open water.

These conclusions, however, have not been borne out by the Logy Bay results. The total power in these data has not yet been interpreted because of a DC offset apparently induced by the FM encoder-decoder. This offset exhibits drift so it is difficult to remove analytically. Further problems exist in the lack of a proper demultiplexing system. Since the multiplexor services each of the four probes for 12 to 16 seconds at a time, it was felt that each individual 12 to 16 second record could be analyzed alone. However, when one looks for the high frequency spectral components, one must use a filter to remove the very strong DC component. It appears that this filter will also remove components above 0.5 Hz unless longer record lengths are used, a suggestion that was apparent from analysis of the Cape Hatt data. Hence, adequate demultiplexing will be required if reasonable power spectra are to be obtained. It is hoped that these improvements in the data analysis will be available before the AMOP conference in June.

The analysis of the Baffin Island data is also not yet completed, although a certain amount of useful information has already been obtained. Figure 6 lends support to the contention that the DC voltage across the probe's electrodes will be greater in a turbulent situation since Figure 6A shows almost twice the DC voltage level of Figures 6B and 6C. The spectra corresponding to the records in Figure 6 are shown in Figure 7. While Figure 7A has components of at least 10^{-5} machine units (volts^2) out to 5 Hz, only the very low frequency components of Figures 7B and 7C are on this order. The spectra of Figures 7B and 7C required an expansion of the vertical axis by a factor of 40 before they could be represented in the figure. Since Figure 7A corresponds to a turbulent situation while Figures 7B and 7C do not, this indicates that the high frequency turbulent tail in the power spectrum has been observed as predicted.

While in Figures 6 and 7 the presence of turbulence may be inferred qualitatively, can one quantify the turbulence present with any accuracy? As of now, difficulties are still being encountered. It seems necessary to add an analogue processing capability to take the 5/2th power of the data (remember that the probe measures the 2/5th power of the data). Without this, the data are artificially smoothed out and high-energy events are obscured.

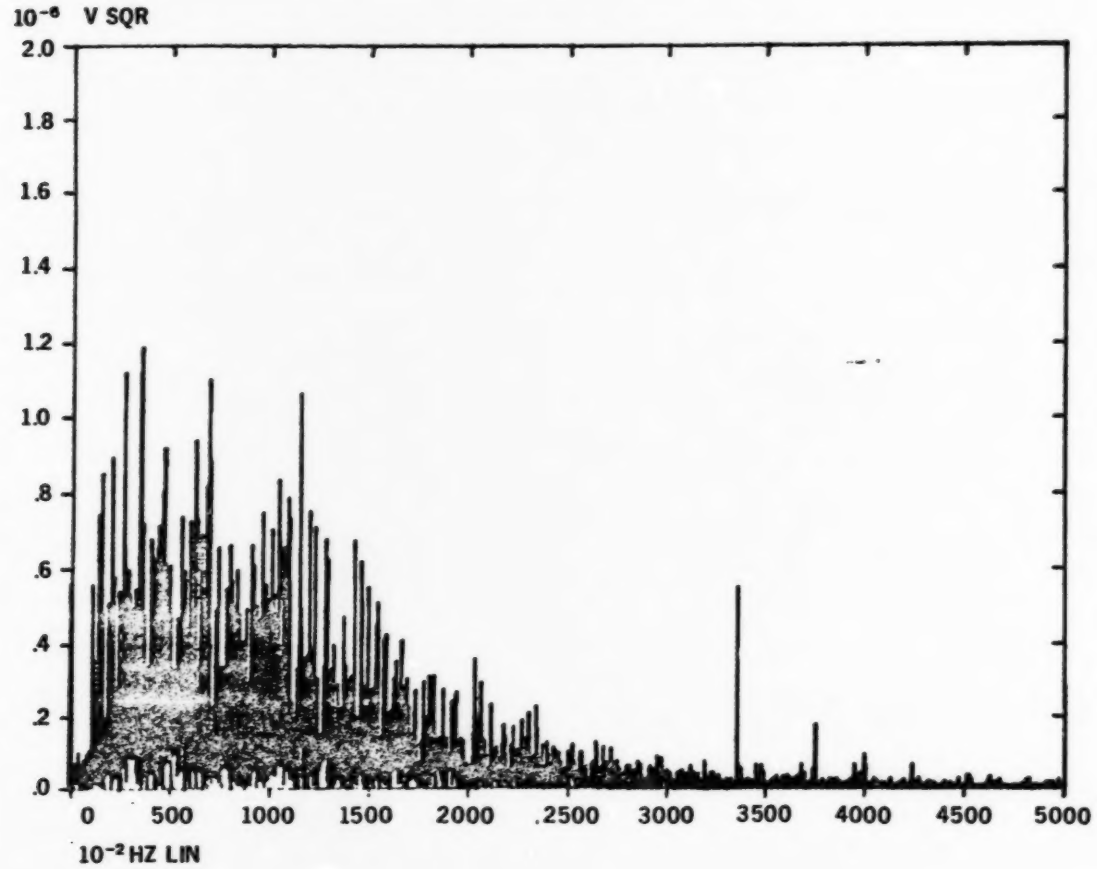

FIGURE 5 POWER SPECTRUM FROM WEIR-TYPE TANK CONSTRUCTED AT C-CORE TO SEE IF ONE COULD GENERATE CONTINUOUS SPECTRA OVER 0 TO 10 Hz OR SO AND IF THE DATA ANALYSIS WOULD REFLECT THIS SITUATION

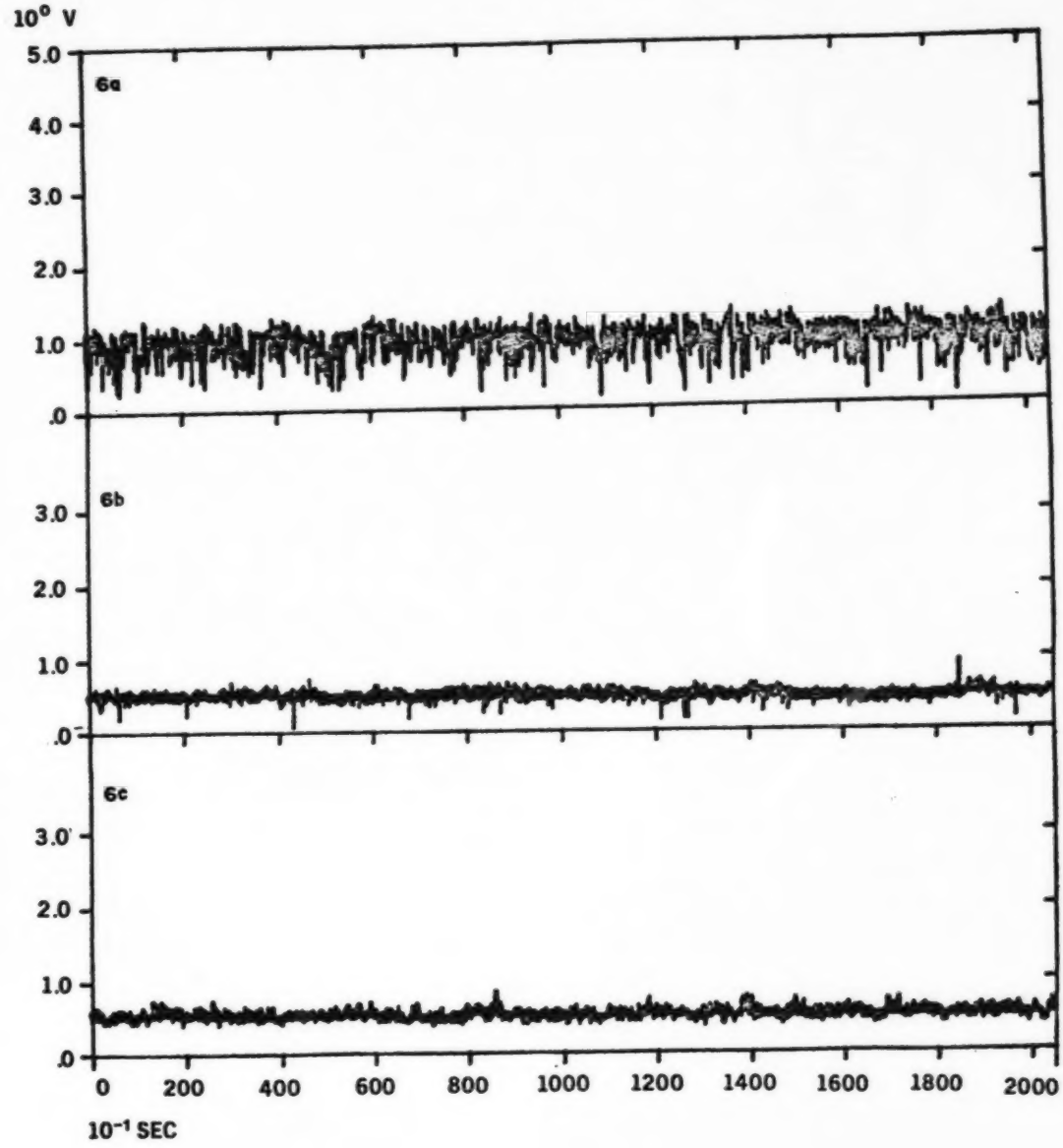

FIGURE 6 RAW DATA TAKEN OVER A 200-SECOND PERIOD AT CAPE HATT, BAFFIN ISLAND
The data in Figure 6A were taken with the probe 1 m deep in 2 m of water. Winds were 20 to 30 knots and swells were estimated to be about 60 cm. Figure 6B was with the probe at the bottom in 1 m of water. Winds were 15 knots. Figure 6C was taken 150 m offshore with probe 5 cm deep. No winds were present. Swells were estimated at 15 to 20 cm. Note the DC offset of the data in Figure 6A relative to the data in 6B and 6C. The total energy in the data of 6A (Equation 4) was 2 to 3 times that of either 6B or 6C.

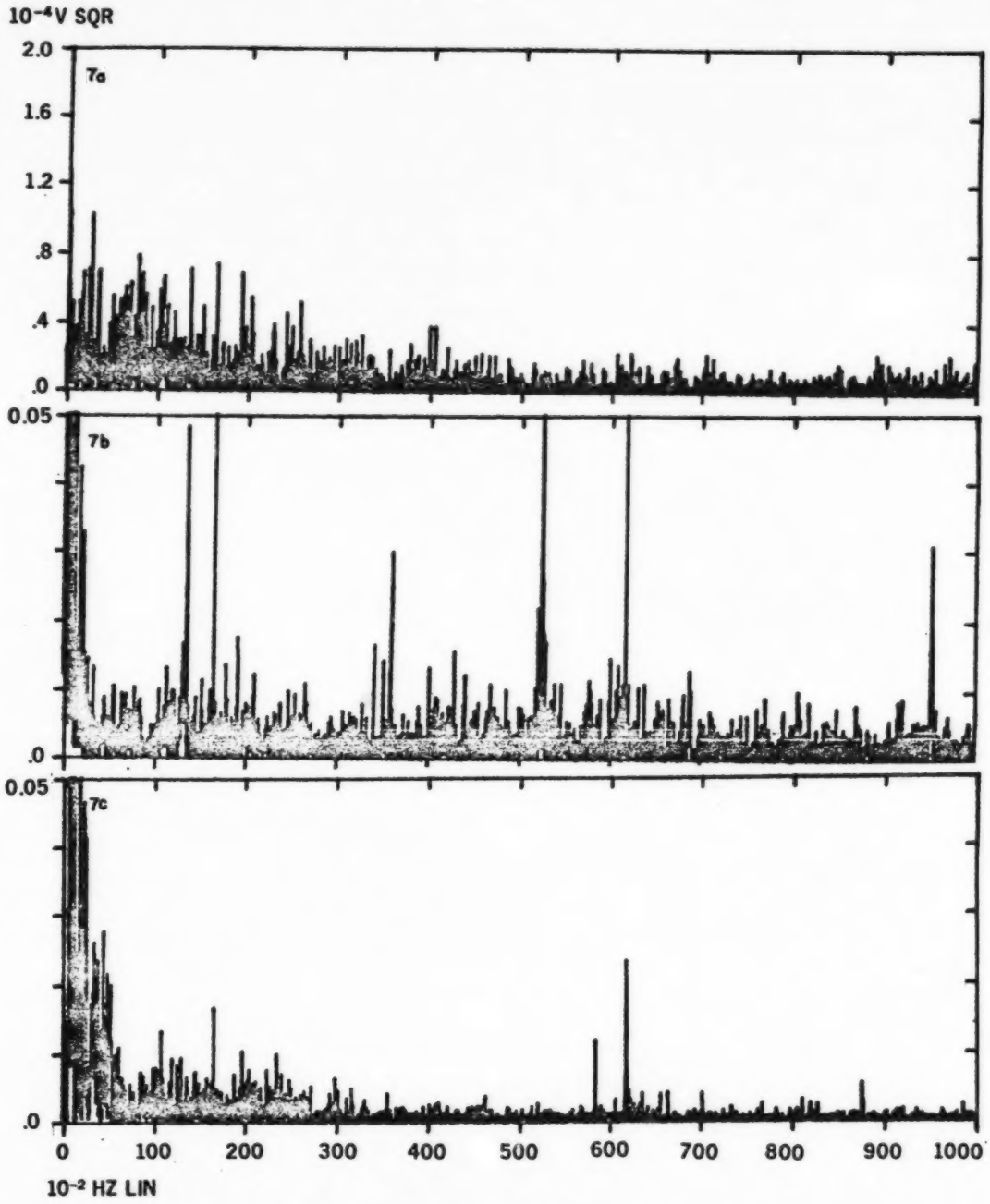

FIGURE 7 POWER SPECTRA CORRESPONDING TO THE DATA OF FIGURE 6 (Figure 7A is the spectrum of the data in Figure 6A, etc.). Note that the energy doesn't die off very rapidly with frequency in Figure 7A while it dies off almost immediately in 7B and 7C. The energy (vertical) axis had to be expanded in 7B and 7C. Their low frequency components (off-scale here) are about 0.4×10^{-4} machine units (volts^2) but their high frequency components are one to two orders of magnitude less than those of the spectrum in 7A.

Lastly, while results such as those of Figures 6 and 7 are encouraging, they are rather ideal and not extremely common. There are many results which are difficult or impossible to interpret. This makes it difficult to establish that DC levels and high-frequency Fourier components increase with turbulence with any real regularity. While the less encouraging results can generally be attributed to weaknesses in the data processing and analysis which are still being corrected, one must emphasize that the ideas presented in this paper are of a preliminary nature. The final verdict on this turbulence-measuring technique will not be in for at least some months.

CONCLUSION

It is apparent that the anemometer system is of some use in determining turbulence characteristics in a controlled environment such as a dispersant test tank. It may therefore be of use in standardizing dispersant tests. The measurement of turbulence in open water is a much more difficult problem. It is hoped that the improvements required in anemometer data processing will make this tool useful in comparing test facilities to the ocean environment.

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